METABK 55(4) 613-616 (2016)
UDC – UDK 621.15:621.791.052:621.78:620.18=111

PROPERTIES AND STRUCTURE OF THE WELD JOINTS OF QUENCH AND TEMPERED 4330V STEEL

Received – Primljeno: 2015-11-20
Accepted – Prihvaćeno: 2016-03-15
Original Scientific Paper – Izvorni znanstveni rad

This work outlines the research on welding of heat treated 4330V steel using the flux core arc welding process. The research describes the effect of preheat temperature, interpass temperature, heat input, and post weld heat treatment on strength, hardness, toughness, and changes of microstructure in the weld joint. Welding with the lower heat input and without post weld heat treatment results in optimal mechanical properties in the weld metal. Austempering at 400 °C results in optimal mechanical properties in the heat affected zone (HAZ). Increasing preheats and interpass temperature from 340 to 420 °C did not improve Charpy V-notch values or ultimate tensile strength in the weld metal or heat affected zones.

Key words: 4330V steel, flux cored arc welding (FCAW), post weld treatment, mechanical properties, structures

INTRODUCTION

Heat Treatable Low Alloy (HTLA) steels are characterized by relatively high strength, high toughness and high hardenability. The high hardenability of HTLA steels ensures high strength across relatively large cross sections, but it also complicates the welding process. The 4330V grade steel is a high strength, high toughness, heat treatable low alloy steel for application in the oil, gas and aerospace industries. It is typically used for large diameter drilling parts where high toughness and strength are required [1]. The welding process for this steel type is difficult by its high hardenability (large amount of alloying elements). In order to ensure high toughness and to prevent cracking, this steel must be welded using a low hydrogen process [2]. Studies of weld metal composition based on AISI 4340 steel indicate that its resistance to solidification cracking can be improved by maintaining the sum of sulphur and phosphorus contents below 0,025 %. Improving cracking resistance also can be obtained by using filler metal with a lower carbon and alloy content [1, 3-8]. Low hydrogen welding procedures must be used with controlled preheat and interpass temperatures to prevent excessive hardness and cracking in the weld metal and HAZ [8-14]. Post weld heat treatment is also used to improve toughness. A common approach to welding HTLA steels is to slow the cooling rate of the weld enough to permit formation of softer bainite instead of hard martensite [1]. Lower bainite is preferred over upper bainite due to its higher toughness [15]. Complete transformation to bainite may not be possible, either due to chemical composition or an inability to maintain high enough temperatures for the required duration [1]. In this case, the weld and HAZ may contain some martensite and retained austenite. Appropriate postweld operations can be used to transform the retained austenite to martensite or bainite.

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EXPERIMENTAL PROCEDURE

Five experiments were performed on quench and tempered 4330V steel. Five Welding Procedure Specifications were used, each using the same filler metal. The 4330V chosen for the experimental research was cold-straightened hardened and tempered bar. It was produced using the electric vacuum degas process. The material has a high hardenability and a martensitic micro-structure. Heat treatment can either temper the martensite or form a martensite-bainite mixed structure. One 25lb spool of 1,6 mm thickness flux core arc welding wire was used for all experiments. The wire was selected based on its similarity in chemical composition to 4330V and its design for high strength high toughness applications. The key differences in chemical composition are lower carbon content and higher nickel content in the filler metal, the intent being to reduce hardenability, improve toughness and maintain comparable strength, Table 1. The transformation temperatures and the expected microstructure are similar in the filler metal and the weld metal.

The weld samples for the experiments were obtained by saw cutting a 255 mm diameter 360 mm long 4330V bar into plates of approximately 25 mm thickness. The plates were then machined to uniform thickness and the appropriate bevel geometry. Five weld procedures were created, one for each experiment. There was a variation in joint type, shielding gas, post weld heat treatment, current, voltage and wire feed speed, Table 2.

Table 1 **Base Metal to Filler Metal comparison for chemical composition, mas. %, C- equivalent**

Plate material	C	Mn	Si	P	S	Cr	Ni	Mo	V	Cu	C_e^*
Base metal	0,31	0,87	0,28	0,007	0,002	0,94	1,93	0,47	0,057	0,16	0,89
Filler metal	0,09	1,12	0,20	0,013	0,009	0,60	3,11	0,50	-	0,72	0,75

Remarks: * - carbon equivalent

Table 2 **Welding procedure specification**

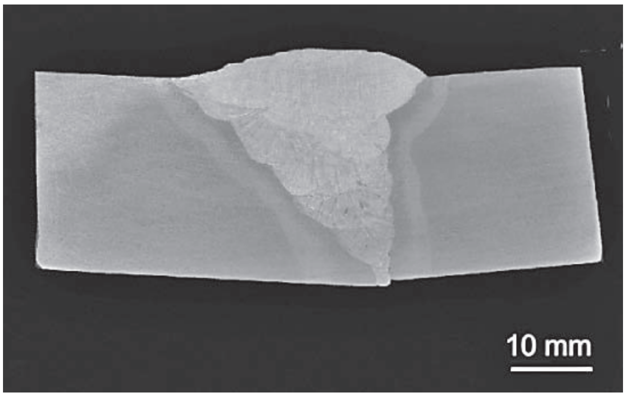
Process specification					
Sample	Joint Type	Shielding Gas	Preheat Temperature / °C	Interpass Temperature / °C	Post Weld Heat Treatment
Sample 1	single-bevel butt	75 %Ar 25 %CO_2	250	250	none
Sample 2	double –V butt	100 %CO_2	340	340	none
Sample 3	double –V butt	100 %CO_2	420	420	none
Sample 4	single-bevel butt	75 %Ar 25 %CO_2	420	420	Austemper 400 °C , 10 hours
Sample 5	double –V butt	75 %Ar 25 %CO_2	420	420	Austemper 400 °C , 10 hours

Remarks: Base material 4330V thickness – 25 mm. Filler metal YS140AC – 1,6 mm, Joint preparation – machine bevel, Polarity – DCEP, Welding position – PA (1G).

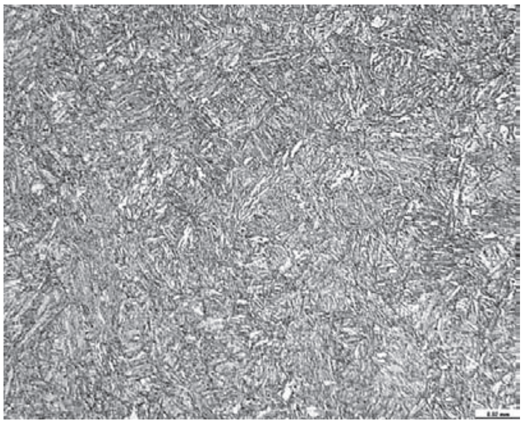
RESULTS AND DISCUSSION

All samples show a tempered martensite structure in the base metal. The heat affected zones and weld metal display mixed structures. The weld metal of sample 4 (austempered) appears to be the least martensitic and likely containing a significant amount of bainite, Figure 1. This was consistent with the results predicted by the isothermal transformation chart.

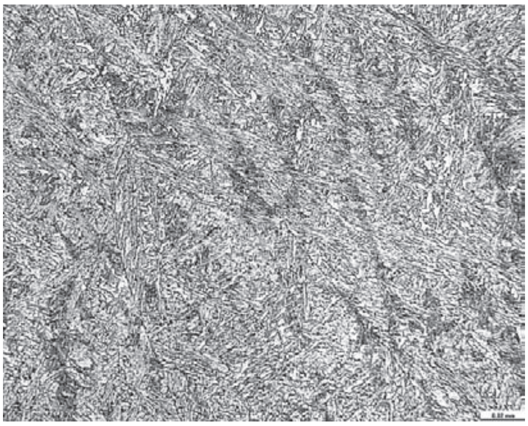
The material inspection certificate from the steel mill for the 4330V used in the experiments indicates 34,4 HRC (~330 HV) 1” (25 mm) below the surface of the bar.



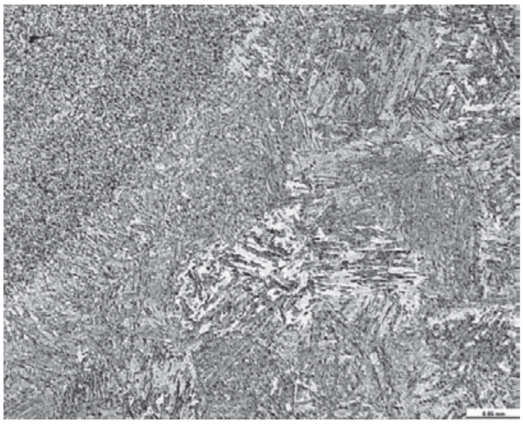
a) Macrograph sample 4, etching Adler



b) Microstructure sample 4, Base metal, 500 x, etching Nital



c) Microstructure sample 4, Weld metal, 500 x, etching Nital



d) Microstructure sample 4 – Fusion line, 500 x, etching Nital

Figure 1 4330V steel macro and microstructure, sample 4

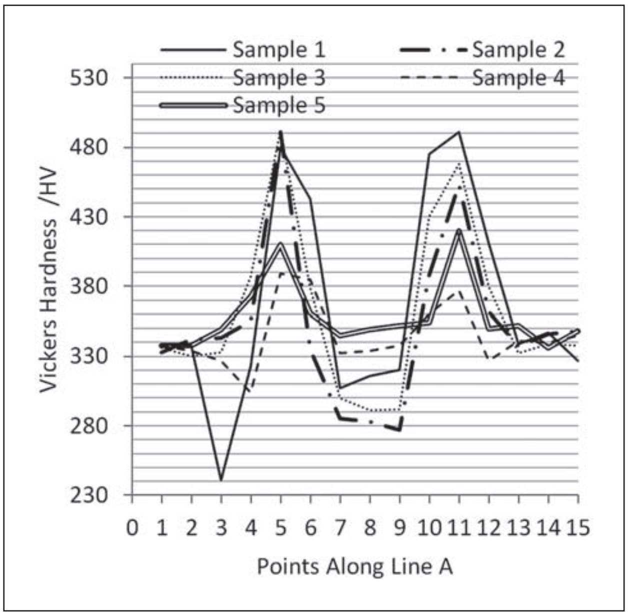


Figure 2 Vickers hardness 2 mm below surface

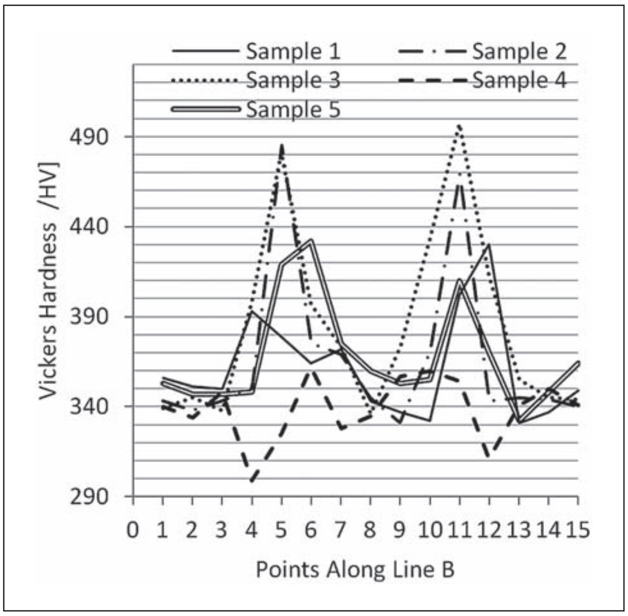


Figure 3 Vickers hardness near root pas

Although the material has a high hardenability, the hardness is expected to be lower further away from the surface and higher closer to the surface, so there will be hardness variation in the plates used for the experiments. Thus the 340 HV average hardness of the base metal in the welded pieces is consistent with the measurements on the material inspection certificate. There was no significant difference in peak hardness in the HAZ between samples 1, 2, 3 (250, 340 and 420 °C preheat/interpass tempe-rature). Sample 3 was welded with a higher heat input and this appears to have enlarged the HAZ. Austempering at 400 °C for 10 hours significantly reduced HAZ hardness down to levels comparable to the base metal. This is likely attributable to the formation of a mixed bainite-martensite structure. Tempering at 400 °C also reduce the HAZ hardness but not to the extent of austempering. There was very little variation in weld metal hardness in samples 1-4, and in these samples the hardness was relatively close to the hardness of the base metal. Sample 5 was tempered at 400 °C and had a significantly higher hardness in the weld metal.

This could have been caused by temper embrittlement, although the most pronounced effects of this phenomenon are generally a decrease in toughness not necessarily an increase in hardness, Figures 2 and 3.

The tensile strength in all samples was very close to the 1 055 MPa ultimate tensile strength of the base metal. Austempering appears to have reduced the tensile strength of the weld metal slightly, which is attributable to the formation of a partially bainitic structure. Tempering did not reduce the tensile strength of the weld metal as would have been expected, it is suspected that the embrittlement in this sample had some strengthening effect, Table 3.

Increasing the preheat/interpass tempe-rature from 340 to 420 °C had no effect on the HAZ toughness. This is likely due to the high hardenability of 4330V. Tempering at 400 °C for 10 hours also did not improve the HAZ toughness. The base material was originally tempered at 620 °C, it is probable that a temperature of 400 °C was insufficient to temper the HAZ. Austempering at 400 °C did significantly improve HAZ toughness, likely due to the toughness of the bainitic structure. Tempering and austempering both reduced the weld metal toughness, Table 3. The presence on Cr, Ni, Mn, the relatively long time spent between 375 °C and 575 °C, and slow cooling in this temperature range makes it likely that the toughness loss was due to temper embrittlement.

CONCLUSIONS

Of the five experiments, welding with the lower heat input and no post weld heat treatment resulted in optimal mechanical properties in the weld metal. Joints (sample 2) had a 1 055 MPa ultimate tensile strength and 26,7 J Charpy V-notch at -40 °C in the weld metal. Austempering at 400 °C resulted in optimal mechanical properties in

Table 3 **Strength properties of welded joints**

Sample	Tensile strength		Impact strength	
	R_m / MPa	Location	V-Notch weld / J	V-Notch HAZ / J
Sample 1	Welded joint did not meet the requirements of ISO 5817			
Sample 2	1 055	Weld	26,7	18,7
Sample 3	1 030	HAZ	23,3	18,9
Sample 4	990	Weld	14,0	24,0
Sample 5	1 025	Weld	14,6	18,6

the HAZ. Increasing preheat and interpass temperature from 340 to 420 °C did not improve Charpy

V-notch values or ultimate tensile strength in the weld metal or heat affected zones. The higher temperature increased the width of the heat affected zone. Austempering at 400 °C reduced HAZ hardness to a level comparable to the base metal. Both tempering and austempering at 400 °C for 10 hours reduced toughness in the weld metal.

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Note: The responsible translator for English language is Translation Bureau “TRANSLATIUM”, Wroclaw, Poland